Final Report

Project: AOARD-10-4088 "**Study on Active Terahertz Metamaterials**"

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Title: Study on Active Terahertz Metamaterials

Background: "Metamaterial" is defined as an artificially structured electromagnetic material exhibiting extraordinary response to the electromagnetic radiation that is hardly performed in natural fashions. Study on "metamaterial" is now one of the emerging science and engineering fields [1-3]. "Terahertz (THz)" stayrtzing in between radio and optical frequencies is still an unexplored, but now becoming one of the hottest frequency bands [4] to creating new "active" metamaterial systems [5]. In [5], Chen et al., first demonstrated an "active" transmittance control by 50% of THz radiation by implementing an arrayed semiconductor metamaterial structure including Schottky diodes. This is an excellent first-step ignition, but fundamental improvements/breakthroughs are necessary to explore deeper science and technology hidden behind the presence. On such a background, two dimensional plasmons (2DPs) in submicron transistors have attracted much attention due to their nature of promoting emission/detection/manipulation of electromagnetic radiation in the THz range [6-10]. In 2009 FSY under the AOARD Grant 09-4013, the grantee investigated THz radiation sources and modulators formed by active metamaterials made with the grantee's original interdigitated grating gate (DGG) structures on 2DP-HEMT device layers (Fig. 1). The grantee continues the research as the follow-on work, consisting of the following two subjects: 1) completion of the verification and enhancement of the coherent monochromatic emission from the high-Q cavity DGG-HEMT, and 2) experimental verification of plasmon-resonant-type THz intensity modulation.

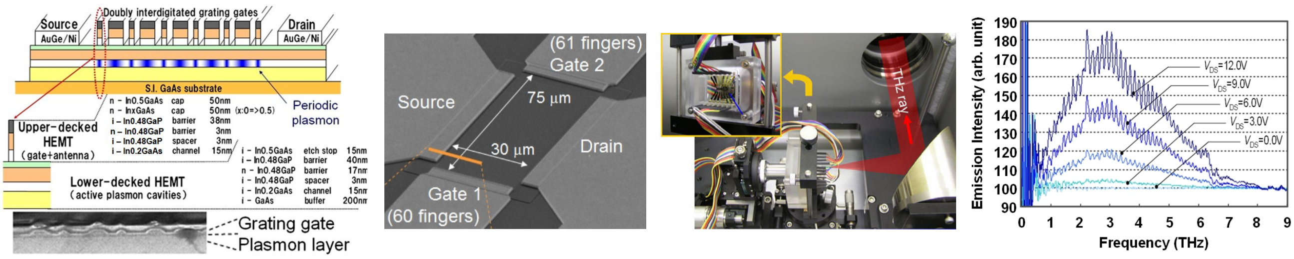

Fig. 1. GaAs-based plasmonic Emitter: structure, SEM image, FTIR setup, and measured spectra.

Results obtained:

1) Trial for coherent monochromatic emission from the high-Q cavity DGG-HEMT

In this program the grantee investigated THz radiation sources and modulators formed by active metamaterials made with the grantee's original interdigitated grating gate (DGG) structures on HEMT device layers. The principle of operation is the 2DPs which are confined into artificial dimensions of metamaterial structure in a HEMT and are electrically or optoelectronically excited to seed the electromagnetic radiation. The basic structure of the grantee's original is focused on (see Fig. 1). Incorporating a high Q cavity installation, injection-locking by photomixed dual-laser irradiation was pursued to realize THz emission of coherent monochromatic radiation. The vertical cavity structure was improved in the 2009FSY AOARD program (see Fig. 2). In this year its performance was characterized. As seen in Fig. 3 (right) the cavity Q factor was drastically enhanced having finess ranging 20-60. We first observed its free-running emission spectra. The results are shown in Fig. 4. Although its radiation spectra exhibited a different aspect depending on the FTIR equipment we confirmed its effect on spectral narrowing (see Fig. 4 (left)). Then optical injection locking was tried. A typical result is shown in Fig. 5. Asymptotic behavior of frequency/phase synchronization was observed. With increasing the radiation power the Δf component increases, attracting the surrounding frequency components although

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14. ABSTRACT
In this program the grantee investigated THz radiation sources and modulators formed by active metamaterials made with the grantee?s original interdigitated grating gate (DGG) structures on HEMT device layers. The principle of operation is the two-dimensional plasmons which are confined into artificial dimensions of metamaterial structure in a HEMT and are electrically or optoelectronically excited to seed the electromagnetic radiation.

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complete injection locking was not obtained.

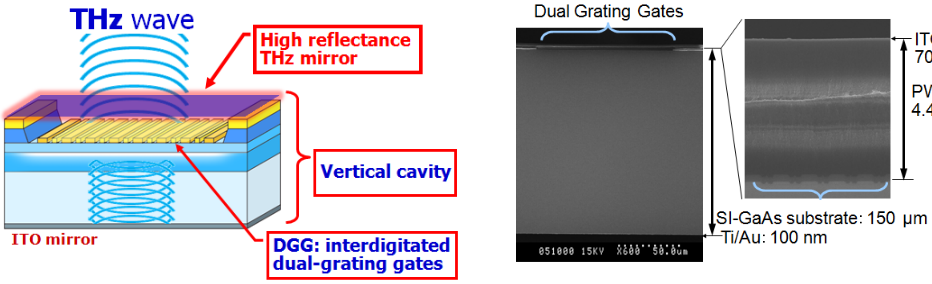

Fig. 2. Schematic view (left) and cross sectional SEM images (right) of the high-Q vertical cavity installed in a DGG- HEMT. PW1500 transparent resist is coated, then ITO is deposited.

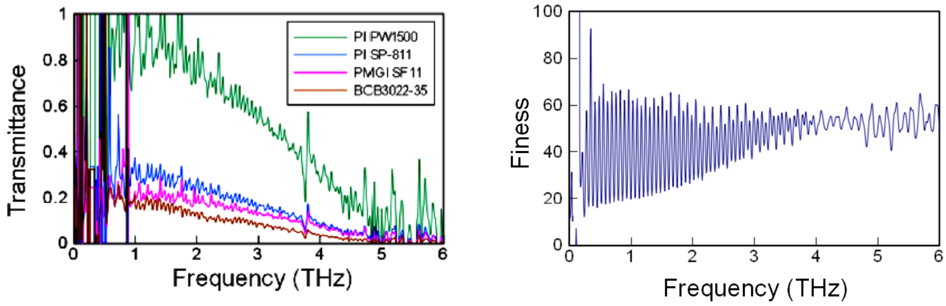

Fig. 3 Left: transmittance of the PW-1500 resist for use in the cavity fabrication in comparison with other materials. FTIR measurement assures the highest transmittance of PW-1500 in THz range. Right: measured cavity performance (finess) of the fabricated vertical cavity structure.

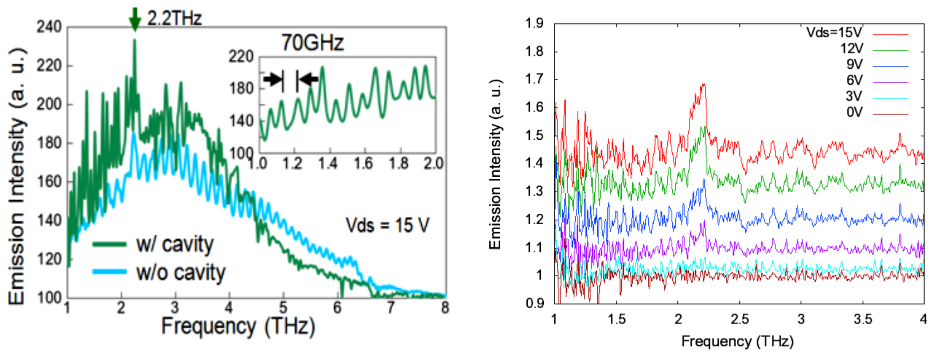

Fig. 4. DC-biased free-running emission spectra. Left: measured by using a JASCO's FTIR. Right: measured by using a Bruker's FTIR.

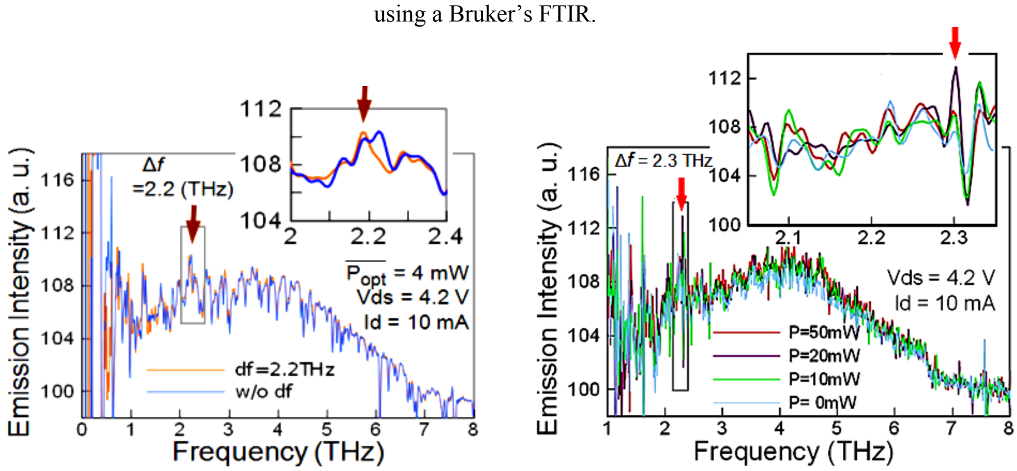

Fig. 5. Ttrial of optical injection locking at 2.2 THz (left) and 2.3 THz (right) using dual laser photomixing.

In photomixing operation, two photons (generally having close but not equal energies) are mixed to excite the difference frequency Δf component in the physical substance. It is a kind of nonlinear process. Photogenerated carriers cannot respond to ultrafast infrared electric-field intensity alteration but can respond to relatively low different frequency components in the THz or below range. Thus photocurrent of the different frequency component can be generated. This will perturb the originally existing plasma waves. Due to the plasma wave nonlinearity the random frequency components of plasma waves close to the delta-frequency will be attracted to the Δf component to be synchronize. This is a so-called optical injection locking. We formulated the physical modeling of the injection locking of our plasmon-resonant HEMT devices.

When the 2D electron systems originally having random frequency components are injection-locked to the Δf component, 2D plasma-wave dynamics is expressed by the continuity equation and Euler equation as follows:

$$\left.\begin{aligned} &\frac{\partial n}{\partial t} + \frac{\partial}{\partial x}(nv) = I_0\left(g_0 + \mathrm{Re}\, g_{\Delta f} e^{i\Delta f t}\right), \\ &\frac{\partial v}{\partial t} + \frac{1}{\tau}v + \frac{s^2}{n_d}\frac{\partial n}{\partial x} + \frac{1}{2}\frac{\partial v^2}{\partial x} = 0, \end{aligned}\right\} \tag{1}$$

where n and v are local density and velocity of electrons respectively, I_0 is the photon flux density, g_0 is the quantum efficiency, τ is the electron momentum relaxation time. The local density and velocity of electrons can be expressed as follows:

$$\left.\begin{aligned} n &= n_0 + n_{\Delta f}(t,x)e^{i\Delta f t} + n_{2\Delta f}(t,x)e^{i2\Delta f t} + c.c., \\ v &= v_0 + v_{\Delta f}(t,x)e^{i\Delta f t} + v_{2\Delta f}(t,x)e^{i2\Delta f t} + c.c. \end{aligned}\right\} \tag{2}$$

where n_0 and v_0 are DC components of the density and velocity of electrons respectively and $n_{i\Delta f}$, $v_{i\Delta f}$ (i: integer) are the i-th harmonic amplitude of density and velocity of electrons respectively. Substituting (2) into (1) the 2D plasma-wave dynamics is expressed by the time-derivative of $n_{i\Delta f}$ and $v_{i\Delta f}$. If the injection locking is performed, no frequency components except for Δf exists. As a consequence, the condition to satisfy the injection locking is given by:

$$\frac{\partial n_{\Delta f}}{\partial t} = \frac{\partial v_{\Delta f}}{\partial t} = 0\,. \tag{3}$$

If the equations have any solutions of non-zero real values when satisfying (3), it is the case of injection locking. We show a new way to numerically analyze the characteristics of the device regarding the injection-locked THz generation.

2) Experiments of THz intensity modulation using the DGG HEMT without vertical cavity structure

In terms of the intensity modulators, the controllability of the transmittance of the 2D plasmonic plane in the DGG-HEMT was numerically analyzed in 2009FSY AOARD program. The finite difference time domain analysis demonstrates that the coupling of THz electromagnetic waves and 2DPs changes with the electron drift velocity and with the sheet electron density in 2DPs (see Fig. 6). The analysis also reveals that the intensity of transmitted waves can be modulated over a wide THz range with an extinction ratio beyond 60% by optimizing the sheet electron density and the drift velocity under nominal area-factor condition (ratio of the 2DP area over the total active channel area) up to 0.6 [11].

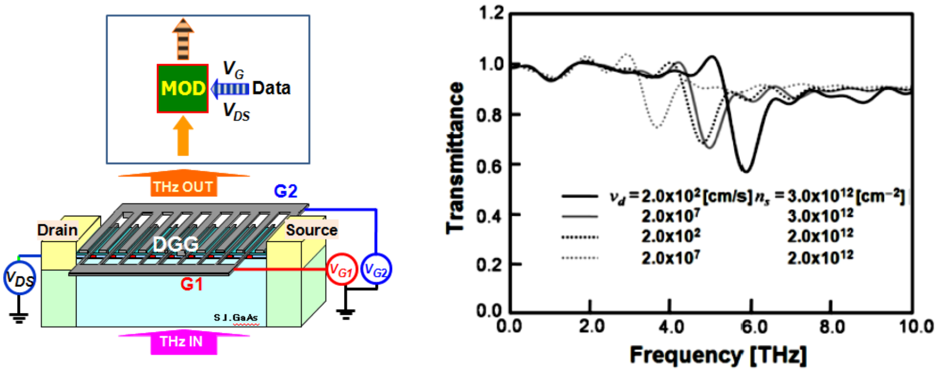

Fig. 6. Schematic of a DGG-HEMT intensity modulator (left) and its simulated transmittance spectra of a DGG-HEMT for various electron drift velocities: v_d and sheet electron density: n_s.

Unfortunately due to the East-Japan quake&tsunami disaster on March 11th 2011, further study on experiments could not been conducted.

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